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PRELIMINARY INVESTIGATION TO DETERMINE THE FEASIBILITY OF ELECTROMAGNETICALLY STIMULATING CARDIAC TISSUE

J. C. Toler and E. C. Burdette

Prepared For
UNIVERSITY OF MIAMI
CORAL GABLES, FL 33124

Under
Purchase Order No. D10244

Submitted By
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FOREWORD

The research efforts described in this report were undertaken by personnel in the Biomedical Research Group in the Electromagnetic Effectiveness Division of Georgia Tech's Engineering Experiment Station. These efforts were sponsored by the University of Miami under Purchase Order No. D10244, and was designated by Georgia Tech as Project A-2001. The period of performance for the research was 2 May 1977 to 2 August 1977.

This research program was possible through the combined efforts of several people at the Veteran's Administration Hospital in Miami, Fl. and at the Georgia Tech Engineering Experiment Station. The authors would like to specifically thank Dr. Ralph Lazzara and Mr. Ed Berberi of the VA Hospital and Mr. John Jones of Georgia Tech, all of whom contributed to the efforts undertaken during the program.

Respectfully submitted,

James C. Toler
Project Director

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Fred L. Cain
Chief,
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INTRODUCTION

In 1477, Vincent de Beauvais reported the earliest account of the stimulating effect of electricity conducted over a wire and into the human body [1]. Interestingly enough, the event in which this electrical stimulation was observed involved Greek fishermen using a trident to spear fish. Vincent de Beauvais wrote that, when certain fish were speared, a "stupor or loss of sensation travels through the pole and reaches the hand of the fisherman who holds the hook. Straightaway, his whole body becomes numb unless he quickly drops the hook." Since that time, interest in the effects, development, and application of electrical stimulation has continually grown, as is evident in the fact that the New York Academy of Science sponsored an international conference on the subject in 1973 [2]. This conference focused on the electrically mediated growth and response mechanisms in living systems.

Interest in electrically mediated growth mechanisms is generally directed to the potential for cell regeneration and wound, nerve, and bone healing. Similarly, the interest in electrically mediated response mechanisms is generally directed to the potential for controlling the complex biologic processes associated with organ functioning. An example of an electrically mediated response mechanism of current interest is stimulation of cardiac function via an electronic pulse generator. Such a generator is typically implanted in a convenient thoracic position and its leads extend into malfunctioning regions of cardiac tissue. When this tissue is incapable of providing a sufficient cardiac stimulus, the electronic pulse generator provides an excitation signal that results in cardiac functioning.

The efforts undertaken during this program represented a preliminary investigation to determine if an externally applied electromagnetic field could provide a cardiac stimulus sufficient to initiate cell depolarization. To be successful, the electromagnetic field would have to excite an ionic

current flow capable of increasing cell potentials by approximately +30 millivolts, i.e., from their -90 millivolt resting potential to approximately -60 millivolts. If this +30 millivolt change in potential could be induced in even a few cells, then cell depolarization would continue without any further stimulus until a potential of approximately +20 millivolts is reached. A repolarization cycle would follow depolarization, and the cells would again attain their -90 millivolt resting potential.

The attractiveness of a cardiac stimulation technique using electromagnetic fields lies in the possibility that stimuli can be non-invasively applied in a manner that does not require electrical contact with the patient. Such a technique would have significant advantages over conventional techniques which require the attachment of metal electrodes to the patient through low resistance paths. In routine procedures, this can be time consuming and cumbersome. In emergency situations, the time necessary for placing the electrodes and securing the low resistance path is sometimes not available; hence, the desire for a non-invasive technique that does not require direct electrical contact with the patient.

BACKGROUND INFORMATION

A limited literature search for technical papers and articles reporting on earlier efforts to electromagnetically stimulate cardiac tissue revealed that information on this subject was sparse. However, the few papers and articles found were considered sufficiently encouraging to warrant the initiation of an abbreviated feasibility investigation. Summaries of the more relevant of these papers and articles are presented in the following paragraphs as background information.

Frey and Seifert [3] investigated the effect of pulse modulated energy on isolated frog hearts after noting Soviet reports of heart rate change in rabbits correlated with VHF illumination [4,5]. The Soviet reports indicated that small reversible changes in rabbit heart rate occured during illumination with low intensity fields at 2500 and 3000 MHz. These changes were a function of the region of the body illuminated, with head illumination producing tachycardia and body illumunation

producing bradycardia. Later Soviet research [6] reported similar effects when intact frog hearts were illuminated with a 2500 MHz field at 60 $\mu W/cm^2$. The Frey and Seifert investigations used 22 isolated frog hearts illuminated with a pulsed 1.425 GHz field whose pulse duration was 10 microseconds. Pulse rate was synchronized with the P-wave such that illumination occured at the peak of the P-wave, 100 milliseconds after the P-wave, and 200 milliseconds after the P-wave. A statistically significant increase in heart rate was observed when the illumination occured 200 milliseconds after the P-wave. In one-half of the cases, arrhythmias associated with the illumination were also observed. It was concluded that "the data provide a reason for more extensive investigations of the effect of modulated energy on the heart." Further, it was suggested that such investigations "may show this energy to be a useful tool in the study of cardiac function."

In research related to the possibility of electromagnetically stimulating cardiac tissue, Wachtel, et al. [7] investigated the effects of microwave fields on isolated nerve cells by extending earlier work that utilized ganglia from the marine gastropod Aplysia to study neuronal function. The ganglion were positioned in microwave stripline and intracellular glass microelectrodes were employed to record the electrical activity of individual neurons before, during, and after irradiation (the microwave frequency was not given). The most pronounced effect reported was the ability to change the firing pattern of both "beating" and "pulsing" pacemaker neurons with irradiation levels of less than 5 mW/cm^2. In further studies, the relative effects of pulsed versus continuous wave irradiation at 1.5 and 2.45 GHz were investigated. Using pulse widths of 10 microseconds and repetition rates of 1 to 5 kHz, there were no significant differences in the effects of pulsed and continuous wave irradiation. It was noted, however, that the pulse widths used were extremely short compared to the millisecond pulses which normally stimulate nerve cells.

Electromagnetically stimulated cardiac function was observed by Tinney and coworkers [8] using continuous wave 960 MHz irradiation of isolated poikilothermic hearts in Ringer's solution. The effect was bradycardia and it was observed only over a narrow range corresponding to 2 to 10 mW/g of absorbed power by the heart. The fact that the observed effect was bradycardia while generalized heating normally produces

tachycardia suggested the occurence of some athermal mechanism related to the electromagnetic field. When this possibility was investigated, it was concluded that the 960 MHz irradiation caused neurotransmitter release either by excitation of nerve remnants in the heart or by some other unexplained mechanism. This neurotransmitter release produced bradycardia over the restricted range of power absorption.

In contrast to the results reported by Frey and Seifert [3], Liu and coworkers [9] could induce no change in the rate of frog hearts as a result of microwave irradiation. These investigations were conducted in both in situ and isolated configurations. In the in situ configuration, the hearts were irradiated with 100 microsecond bursts of energy at either 1.42 or 10 GHz. The choice of the 1.42 GHz frequency was based on replicating the work by Frey and Seifert. In the isolated heart configuration, irradiation was provided by 100 microsecond bursts of microwave energy at 1.42 GHz. Thirty hearts were irradiated (15 at each of the two frequencies) in the in situ configuration and the energy was delivered to the open thorax using a semi-rigid coaxial microprobe pressed against the pacemaker region of the heart. The R-wave of the heart was used to trigger delivery of the 100 microsecond burst of microwave energy. The isolated configuration involved only one heart which was positioned in a Ringer's solution such that the pacemaker region was accessible to the coaxial microprobe. The burst of 1.42 GHz energy delivered in this configuration was triggered by the P-wave and, in one instance, was delayed by 100 microseconds. Results for the in situ configuration revealed no significant differences in heart rate between periods of irradiation and no irradiation. Similar results were observed for the isolated heart configuration.

Differing from literature that reports results of research investigations is a publication by Frey [10] in which a theoretical basis for non-invasively stimulating neural elements of the brain is presented. This basis assumes that partial rectification in any desired small volume of a high frequency current field produced by appropriate means within the brain will result in a localized tissue stimulus. To accomplish this partial rectification, the simultaneous application of an electric

or magnetic field applied externally to the brain and a focused ultrasonic field localized with the focus at the site of the stimulation is proposed. It is assumed, for the simple case, that the frequencies of these two fields are equal. The traveling acoustic wave has associated with it a propagating alternating temperature variation, and since the conductivity of tissue changes with temperature, the acoustic field will induce a periodic variation in conductivity. The maximum conductivity variation will occur at the focus of the acoustic field. Therefore, when electric (or magnetic) and acoustic fields of the same frequency are simultaneously applied, the current flow in the tissue at the focal point when the temperature is increased above normal (the compressive half-cycle of the acoustic wave) will differ from the current flow in the same location when the temperature is below normal (the rarefaction half-cycle of the acoustic wave). This results in a situation in which the net charge transferred during the compressive and rarefaction half-cycles of the acoustic wave will differ. The magnitude of this unidirectional charge transfer will be determined by various factors including (1) the amplitude of the temperature variation at the acoustic wave focus, (2) the magnitude of the conductivity of the tissue and its coefficient of variation with temperature, (3) the amplitude of the applied electric field, and (4) the magnitude of the acoustic absorption coefficient. Acceptable values of electric and acoustic field parameters are predicted and it is shown analytically that the field values should stimulate cortical pyramidal neurons.

As noted earlier, the available literature concerned with electromagnetic stimulation of tissue was limited; however, this limited literature presents situations in which isolated cardiac tissue and nerve cells have been stimulated in response to electromagnetic field illumination. Based on these efforts, it was decided to undertake a two-day preliminary investigation to determine the feasibility of electromagnetically stimulating <u>in vivo</u> cardiac tissue. The remainder of this report describes the electromagnetic illumination assemblies, the animal configurations , and the information resulting from these efforts.

EQUIPMENT CONFIGURATIONS

This section of the report describes the equipment configurations (four different signal sources and three different illuminators) used during investigations to determine the feasibility of stimulating cardiac tissue using externally applied electromagnetic fields. The applicable frequency range was 10 MHz to 4 GHz in segmented frequency bands. Both continuous wave (CW) and pulsed environments were used to illuminate anesthetized dogs under open-chest and closed-chest conditions. Six different pulse widths (25 microseconds, 50 microseconds, 5 milliseconds, 10 milliseconds, 25 milliseconds, and 50 milliseconds) and pulse rates ranging from 140 to 200 pulses per minute at power levels up to approximately 200 watts were used during the investigations.

In the following paragraphs, a brief discussion of (1) the role of electrical properties in electromagnetic field/biological tissue interactions and (2) illuminator designs for coupling electromagnetic energy into tissue are presented. These discussions are followed by detailed descriptions of the four different equipment configurations.

A. Role of Electrical Properties in Electromagnetic Field/Biological Tissue Interactions

The interactions that occur when living tissue is exposed to an electromagnetic (EM) field can result in either tissue heating, tissue stimulation, or both. These interactions are significantly influenced by the electrical properties (dielectric constant, loss factor, loss tangent and conductivity) of the tissue; therefore, it is essential that these properties and their behavior during irradiation be thoroughly understood.

A convenient point-of-departure in understanding electrical properties is recognition that non-magnetic materials may be characterized by their complex permittivity ε^*. The exclusion of magnetic materials means that the material's permeability may be equated to the free space permeability, μ_o, and therefore need not be a part of subsequent considerations. The complex permittivity ε^* of a material is expressed

mathematically as

$$\varepsilon^* = \varepsilon' - j\varepsilon'' \ , \qquad (1)$$

where the real and imaginary parts are termed the dielectric constant and loss factor, respectively. As a dictionary definition [11], the dielectric constant of a material is "the property that determines the electrostatic energy stored per unit volume for unit potential gradient." Elsewhere [12], the dielectric constant of a material is described as being "equivalent to the capacitance of one centimeter cube, corrected by a constant to account for the units of measurement of capacitance." In both cases, dielectric constant is seen to be the electrical property which defines a material's capability for storing energy during exposure to an electric field. This capability is usually presented relative to the dielectric constant of free space as

$$K = \frac{\varepsilon'}{\varepsilon_o} \ , \qquad (2)$$

where K = relative dielectric constant,

ε' = dielectric constant of the material, and

ε_o = dielectric constant of free space.

Because of the lack of a standardized terminology, the terms dielectric constant ε' and relative dielectric constant K are sometimes used interchangeably. Further confusion in terminology arises when the term complex dielectric constant is used to mean complex permittivity.

In a complimentary manner, the loss factor ε'' is defined as the capability of a material for dissipating energy in the form of heat [13]. Therefore, dielectric constant and loss factor are interrelated electrical properties which describe a material's capability for storing energy during exposure to an electric field, and then dissipating this energy in the form of heat. This definition may be expressed as the ratio of loss factor to dielectric constant. This ratio is termed the loss tangent and mathematically has the form

$$\tan\delta = |\varepsilon^*| e^{-j\delta} = \frac{\varepsilon''}{\varepsilon'} = \frac{\varepsilon''}{K\varepsilon_o} , \quad (3)$$

where $\tan\delta$ = loss tangent,

ε'' = loss factor,

ε_o = dielectric constant of free space, and

K = relative dielectric constant.

The importance of the electrical property termed conductivity is evident in the fact that power absorbed per unit volume is expressed as

$$P = \sigma \frac{E^2}{2} , \quad (4)$$

where P = power per unit volume,

σ = conductivity, and

E = electric field strength.

This conductivity parameter is reflective of all dissipative or loss mechanisms in the tissue.

There are two primary types of EM heating that are important in coupling EM energy into tissue. The first type of EM heating (resistive) is analogous to the heating that occurs in a metal wire that is conducting an electric current. However, in tissues, current flow results from ionic conduction rather than from the movement of electrons [14]. Because biological tissues are resistive, current flow (ionic conduction) in them will generate resistive heating. Resistive heating of tissue is significantly dependent on the electrical properties of the tissue, and, in particular, on the conductivity. The second type of EM heating is known as dielectric heating. This heating modality can be affected by subjecting tissue to a radiated EM field. Again, the role of tissue electrical properties is a major one for they determine the amount of EM energy that will be coupled into the tissue. In this case, the heating is primarily dependent upon the tendency of molecular dipoles to align themselves with the electric field [15].

Tissue electrical properties are conventionally determined by either measuring the reflection coefficient or changing the sample length [15].

The most common method for measuring tissue electrical properties is to use a slotted line attached to a short-circuited transmission line. This measurement configuration is based on determining the reflection coefficient of the in-vitro tissue samples. However, recently a measurement technique has been developed that permits in-vivo determination of tissue electrical properties over a swept frequency range of 10 MHz to 10 GHz [16]. The technique is based on an antenna modelling theorem which states that the change in free space terminal impedance of an antenna inserted into a lossy dielectric medium is related to the electrical properties of that medium. A prototype in-vivo measurement system which utilizes a small probe antenna has been utilized in preliminary measurements of the electrical properties of living canine tissues, including kidney, muscle, and fat. Although preliminary, results of these measurements have proven useful in designing the horn and capacitor plate illuminators used during these investigations.

B. Illuminators for Coupling Electromagnetic Energy Into Tissue

A number of different illuminators may be used to couple EM energy into tissue for the purpose of stimulation initiation. Two of these are:

1. Illuminators that radiate an EM field. The radiated field is coupled into the tissue via dielectric interactions with polar molecules.

2. Illuminators that utilize either insulated or non-insulated plates. The metal plates are placed opposite each other on the tissue surface. The EM coupling results from ionic conduction.

Illuminators based on radiated EM fields usually operate at frequencies in the UHF or microwave bands (frequencies above 300 MHz). At these frequencies, efficient EM coupling can be achieved through dielectric interactions. However, the EM field strength at the higher frequencies ($\geq$ 1 GHz) will decay rapidly as the field travels through the tissue. Therefore, although interaction with polar molecules is high, the effective EM field coupling occurs only in tissues within a few centimeters of the surface.

Illuminators which utilize capacitive coupling are based on the fact that ionic conduction, and therefore current flow, occurs in tissues placed

between two metal plates excited by EM energy. Since tissue is conductive, it is possible to cause a current to flow through the tissue between the metal plates. The coupling mechanism, if the metal plates are non-insulated, is due to the inherent tissue resistance. If the plates are insulated, the EM coupling mechanism is dielectric in nature. Figure 1 depicts the case in which capacitor plates are placed directly against the tissue. If the impedance ($Z = R + jX$) of the capacitor plate/tissue configuration were measured at frequencies in the 10-50 MHz range, the resistance R would comprise the major portion of this impedance. Since R is related to conduction current flow, EM coupling to tissue for the case depicted in Figure 1 will be primarily resistive.

An alternative method for utilizing capacitor plates to heat and/or stimulate tissue involves the dielectric coupling mechanism. If the metal plates are insulated from the tissue by a non-conducting dielectric, as depicted in Figure 2, the reactance X constitutes the major portion of the impedance (frequencies $\geq$ 50 MHz). This implies that only a small conduction current is flowing and therefore, the EM field coupling is primarily dielectric.

C. Equipment Arrangements

Since information on the subject of cardiac tissue stimulation via EM field exposure was sparse, it was deemed advisable to examine the effects of as many parameter variations as possible during this two day investigation; therefore, the four equipment arrangements described below were used.

1. Equipment Arrangement for the 10 to 50 MHz Frequency Range

This equipment arrangement was composed of an AILTECH Model 445 Signal Source with a 10 to 50 MHz plug-in oscillator, a pulse generator, a Johnson KW Matchbox Antenna Tuner, a bi-directional coupler, and two Hewlett Packard Model 435A Power Meters. Electromagnetic energy was delivered using the capacitor plates and a coaxial probe applicator. A block diagram of the equipment arrangement is shown in Figure 3. The maximum power output capability of the signal generator in either the pulsed or CW mode was 50 watts. During these investigations, the output power level was maintained between 30 and 40 watts.

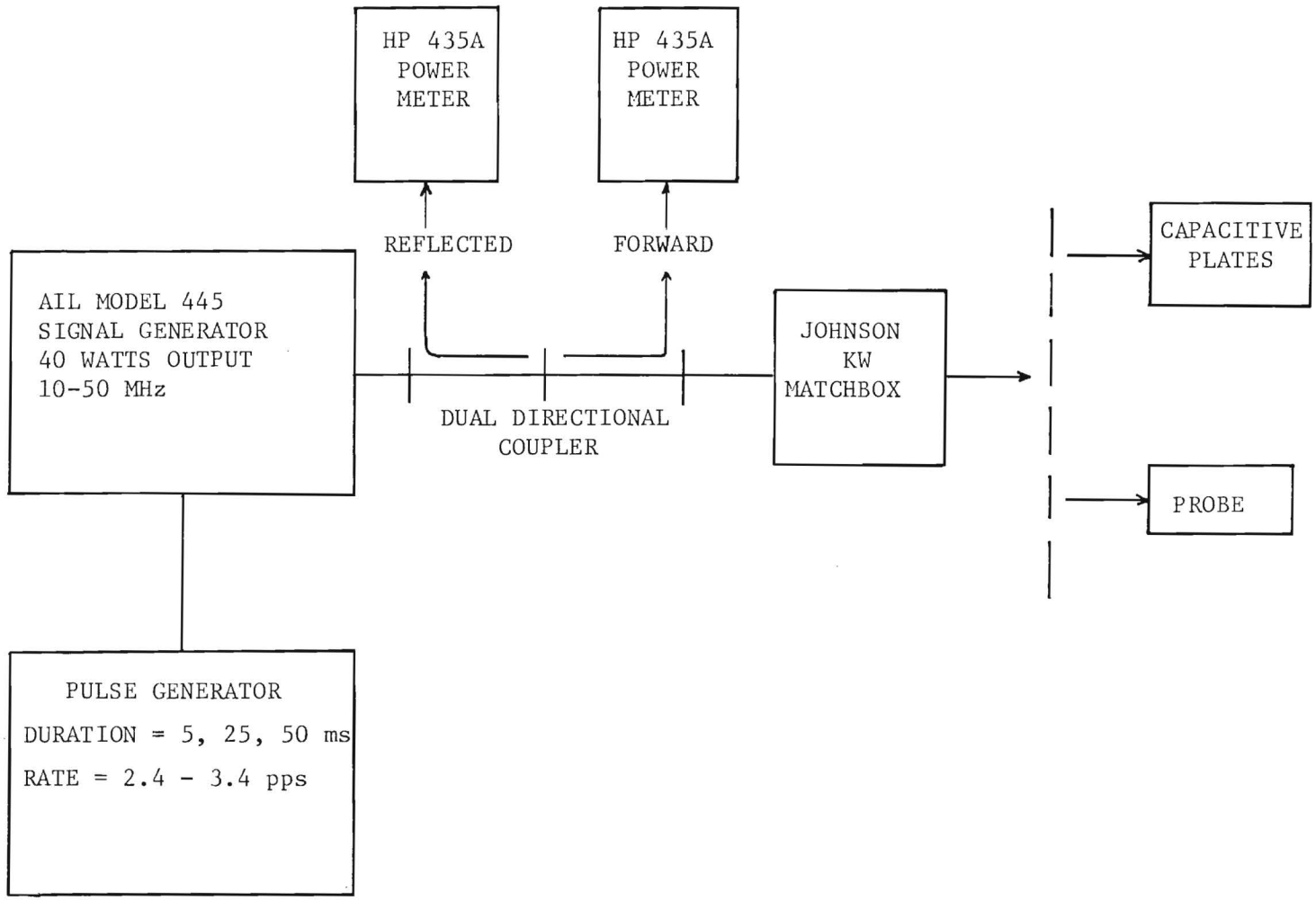


Figure 3. Block diagram of the equipment arrangement used for tissue stimulation in the 10 to 50 MHz frequency range.

The capacitor plate illuminators consisted of pairs of metal plates as shown in Figure 4. It is noted that the nonconducting dielectric material (Teflon) could be either removed from or attached to the smaller plates via the flat-headed bolts. This permitted either ionic conduction or dielectric coupling mechanisms to be readily investigated. A third larger non-insulated metal plate was also used as an illuminator to determine if relative size of the plates affected cardiac response to the EM field.

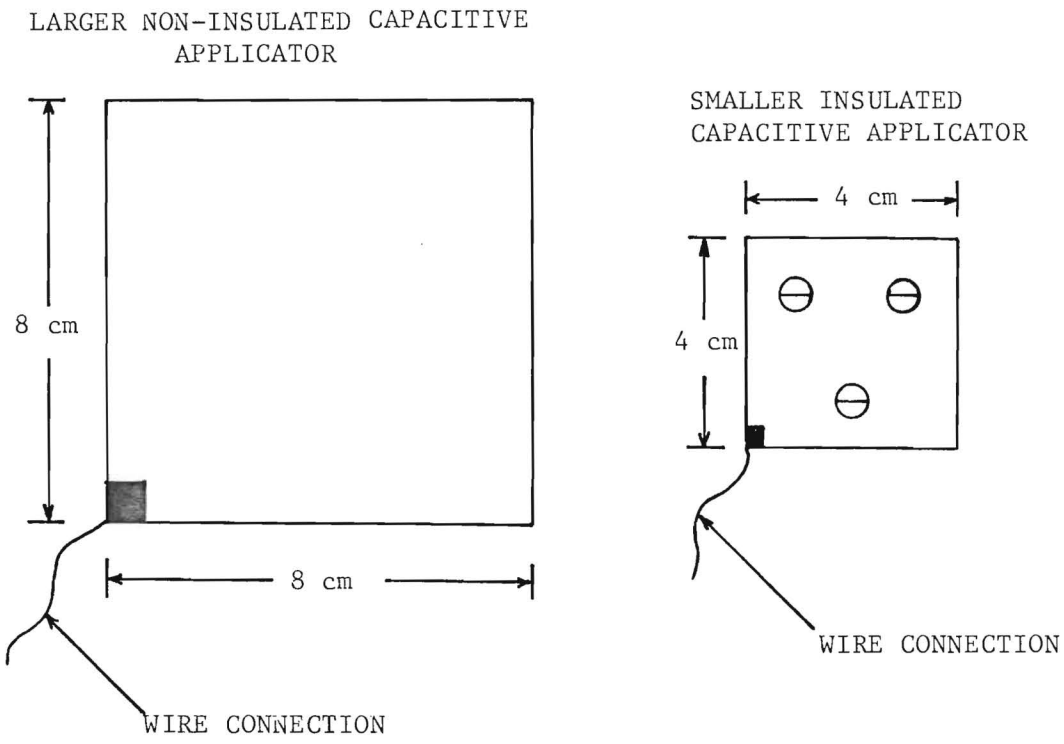
The probe applicator shown in Figure 5 was also used with this equipment arrangement. The center conductor of this probe extended a short distance beyond the outer conductor and a small circular ground plane was soldered to the outer conductor. This short monopole probe permitted direct coupling of EM energy into the cardiac tissue.

2. Equipment Arrangement for the 50 to 200 MHz Frequency Range

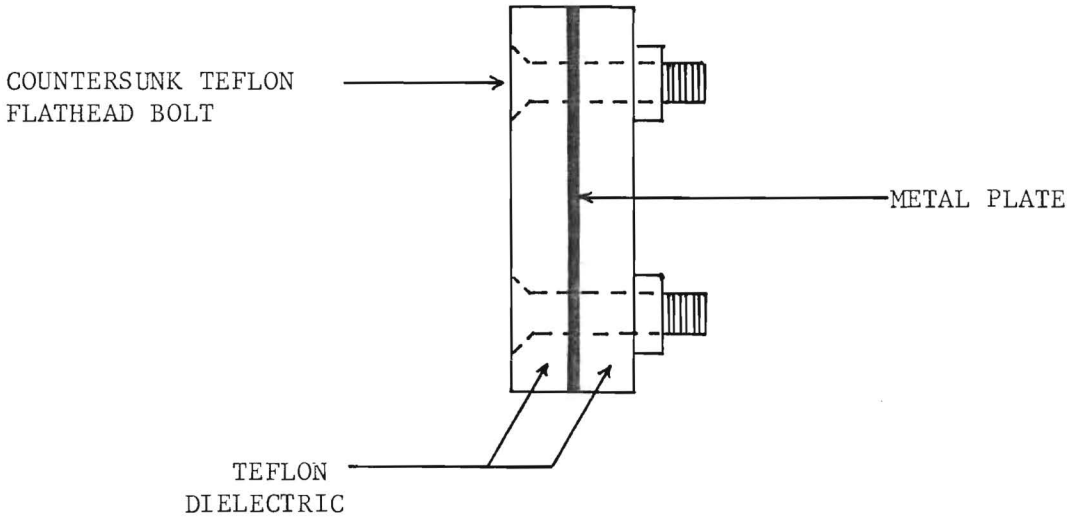
The equipment arrangement employed for this frequency range was identical to that used in the 10 to 50 MHz frequency range with the exception that the 10 to 50 MHz plug-in oscillator was replaced by a 50 to 200 MHz plug-in oscillator and the Johnson Tuner was replaced by a double stub tuner. Figure 6 shows the individual components of this equipment arrangement. Only the capacitive applicators shown in Figure 4 were used with this equipment arrangement.

3. Equipment Arrangement for the 300 MHz to 3 GHz Frequency Range

A majority of the experimental investigations were conducted using the equipment arrangement shown in Figure 7. This arrangement consisted of an AILTECH Model 125 Signal Generator (with interchangeable tubes covering the 300 MHz to 3 GHz frequency range), a pulse generator, two Hewlett Packard Model 779D Directional Couplers, two Hewlett Packard Model 435A Power Meters, and two different types of illuminators. The capacitor plates (both insulated and non-insulated) described earlier were used and, at frequencies in the 1-3 GHz range, the dielectrically loaded horn illuminator detailed in Figure 8 was used. This horn illuminator was an S-band (2 to 4 GHz) waveguide, dielectrically loaded with a silicon based encapsulant mixed with a small amount of titanium powder. The dielectric constant of this mixture was approximately four, which lowered the cutoff frequency of the guide to approximately 1 GHz.



(a) Face view of the capacitive applicators.



(b) Side view of the smaller capacitive applicator.

Figure 4. Metal plate capacitive applicators.

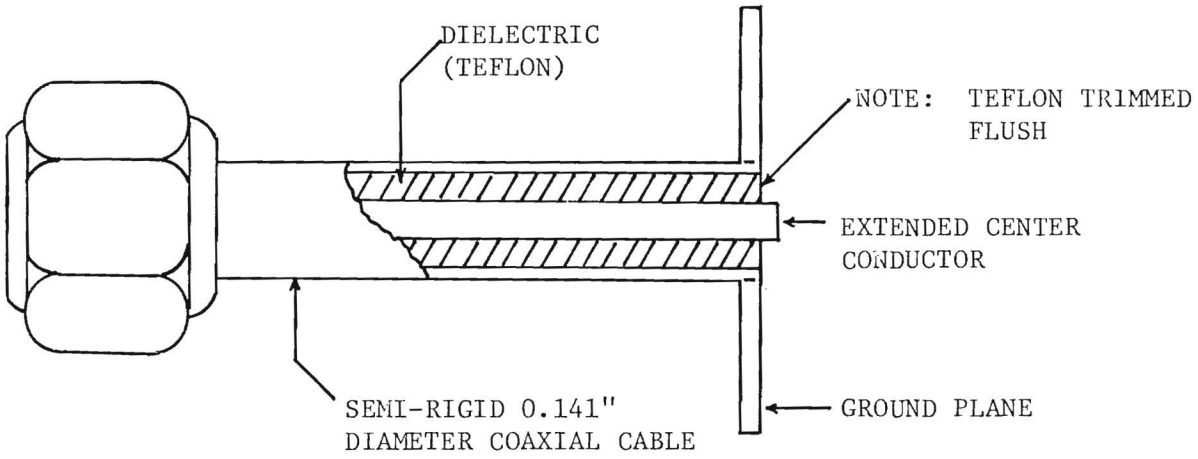


Figure 5. Diagram of in-vivo measurement probe.

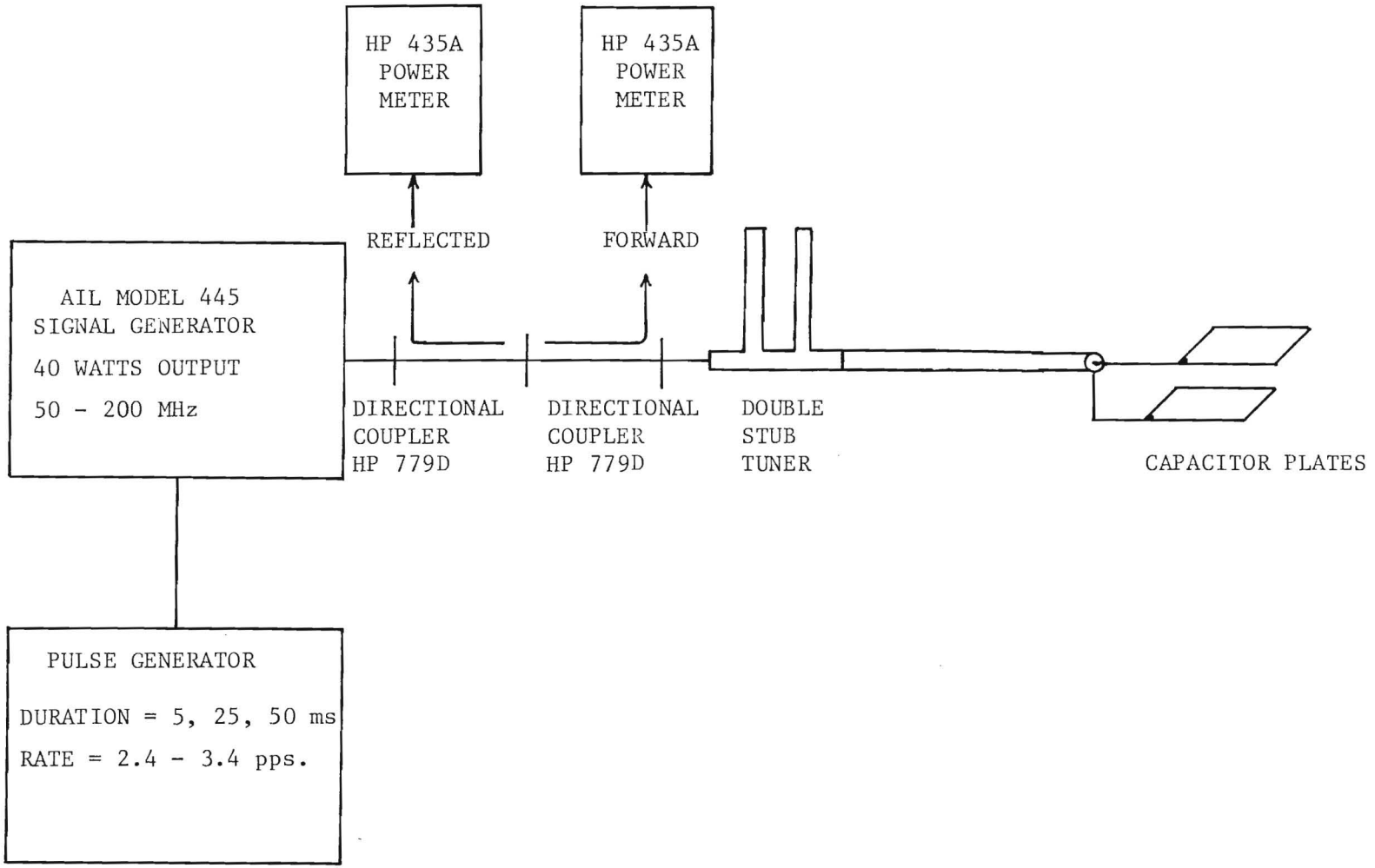


Figure 6. Block diagram of the equipment arrangement used for tissue stimulation in the 50 to 200 MHz frequency range.

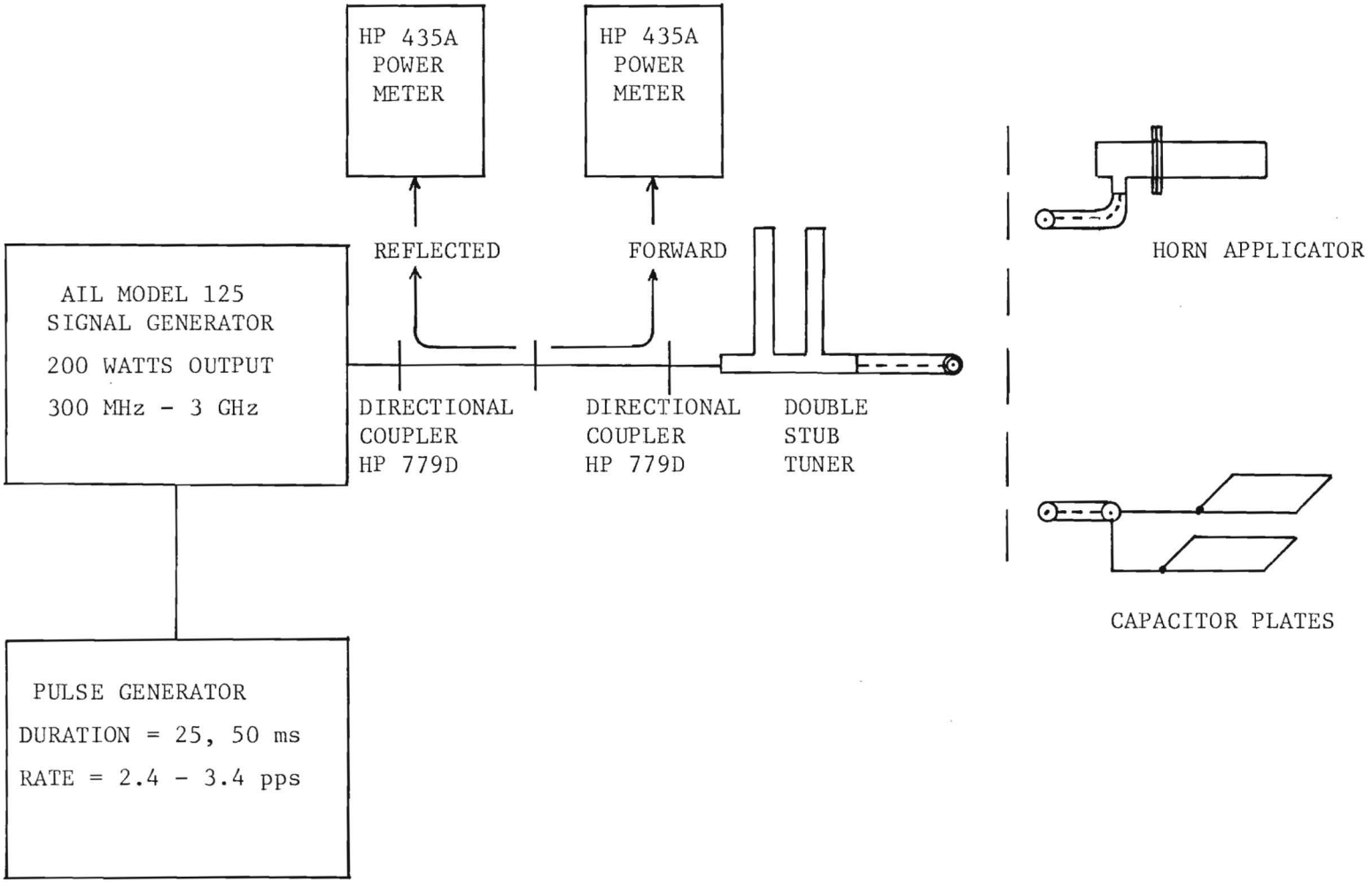
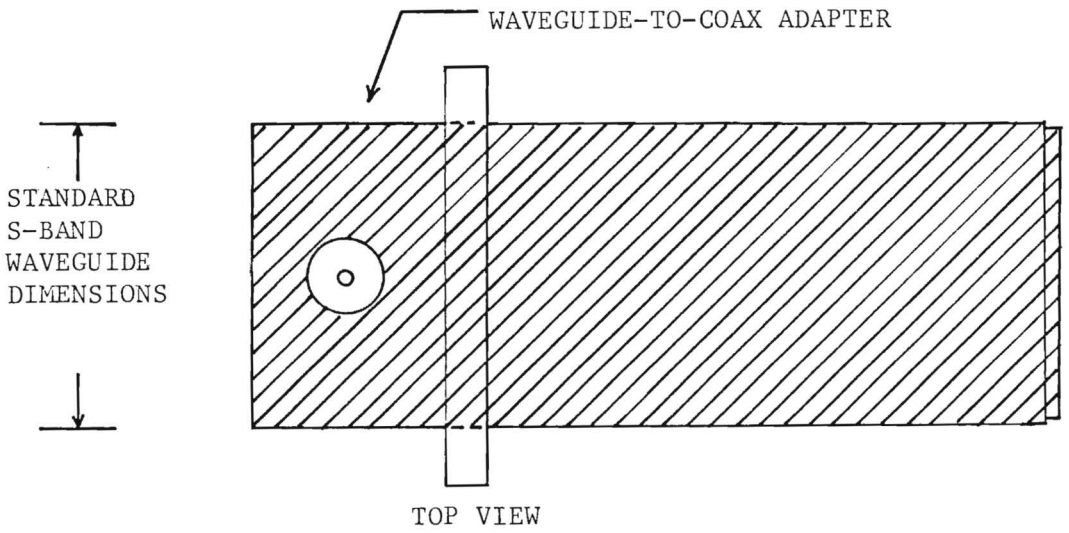


Figure 7. Block diagram of the equipment configuration used for tissue stimulation in the 300 MHz to 3 GHz frequency range.



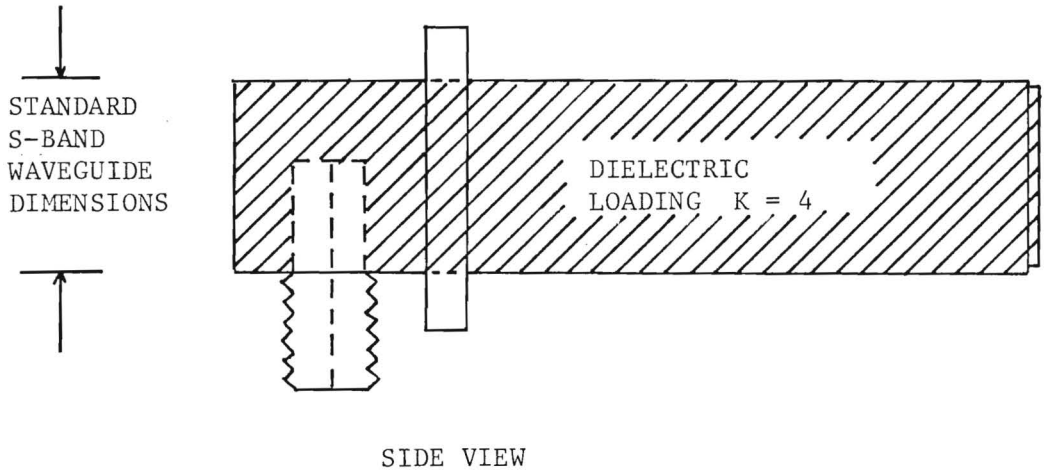


Figure 8. Detailed diagram of the dielectric-loaded horn applicator used for investigations in the 1-4 GHz frequency range.

4. Equipment Arrangement for the 2 to 4 GHz Frequency Range

The equipment arrangement for this frequency range was configured about a Winschel Model 430A Sweep Generator and a Hughes Model 1177H Traveling Wave Tube (TWT) Amplifier. The block diagram in Figure 9 shows the interconnection of individual equipments. Only the dielectrically loaded horn illuminator was used to deliver EM fields to the cardiac tissue during investigations in this frequency range.

For each of the above described equipment arrangements, both forward and reflected power levels were continuously monitored during tissue irradiation. For each type of illuminator, the reflected power was tuned to the minimum level attainable in order to provide delivery of the maximum possible power to the tissue. Experimental investigations performed using these four equipment arrangements are described in the following paragraphs.

EXPERIMENTAL INVESTIGATIONS

This section of the report describes the experimental investigations undertaken to determine the feasibility of stimulating cardiac tissue using an externally applied EM field. All investigations were conducted over a two day period in one of the Surgical Research Labs of the Atlanta Veteran's Administration (VA) Hospital. Prior to the initiation of the two day investigation, the required test equipment and instrumentation were transported to the VA Hospital and interconnected as shown in the previous section of this report. The morning of the first day was devoted to planning the final protocol and preparing the dog. Detailing the final protocol was difficult because it was planned that each step would be dictated largely by the results of the previous step. However, the overall protocol outline used during the experimental investigation was structured as follows:

1. The EM signal sources and associated monitoring/control instrumentation were assembled in the Surgical Research Lab and checked for satisfactory operation.

2. The dog was anesthetized and prepared for experimental procedures that first involved closed chest investigations. Open chest investigations followed most of the closed chest investigations. All investigations consisted of

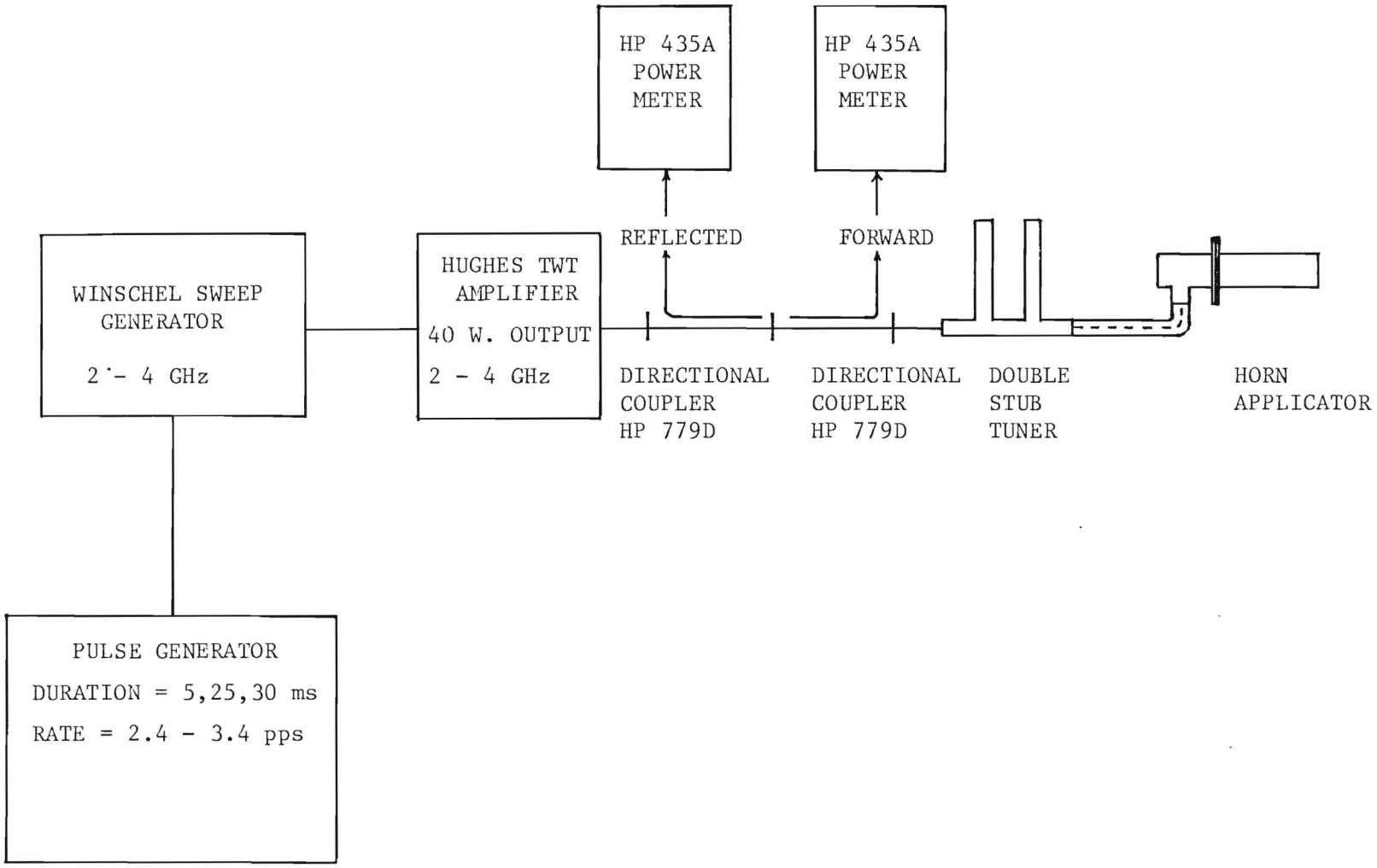


Figure 9. Block diagram of the equipment configuration used for tissue stimulation in the 2 to 4 GHz frequency range.

attempting to induce premature ventricular contractions in the normally functioning heart. No effort was made to synchronize pulsed irradiations with any phase of the heart cycle.

3. Cardiac function was continuously monitored using a multi-channel ECG recorder, and a permanent record of heart activity was obtained.

4. EM irradiation of the heart area was initiated in the closed chest configuration as the ECG record was observed. Different illuminators, as applicable, were used while the power level, pulse parameters, frequency, and illuminator position were varied.

Throughout the experimental investigations, the actual field strengths to which the cardiac tissue was exposed were determined in a qualitative manner only. A quantitative determination of these field strengths would be beyond the scope of this preliminary investigation because the experimental configuration is one in which non-planar fields from non-standard radiating elements are incident on a non-homogeneous dissipative medium. Therefore, a precise determination of field strength would require rather extensive analytical and experimental efforts. It is noted that these more extensive efforts would be undertaken in an expanded program if these investigations showed cardiac response to an external EM field to be feasible.

Initially, the equipment arrangement shown in Figure 9 was used to provide CW irradiation in a closed chest configuration with the 2 to 4 GHz frequency range covered in 200 MHz steps. With the dielectrically loaded horn in direct contact with the chest and with a power level of approximately 40 watts, tissue heating was observed. Because of the desire to minimize stress to the dog, CW irradiation was discontinued in the closed chest configuration. The chest was then opened and the horn illuminator was positioned in close proximity to the exposed heart. The irradiation under these conditions included both CW and pulsed fields. The pulse parameters were 5, 10, 25, and 50 millisecond pulse widths with rates variable from 2.4 to 3.4 pulses per second (approximately 140 to 200 pulses per minute). Again, a wide range of pulse width, pulse rate, frequency, power level, and illuminator positions were used in an effort to influence

cardiac functioning. These investigations were then repeated in the open chest configuration using the capacitor plates as illuminators. Both insulated and non-insulated plates were positioned against cardiac tissue during irradiation with a variety of pulse width, pulse rate, frequency, and power level combinations.

The equipment arrangement shown in Figure 3 was used for experimental investigations in the 10 to 50 MHz frequency range. Ten megahertz frequency increments were used with both the capacitor plate illuminators and the monopole probe applicator. Both insulated and non-insulated capacitor plates were used, with one plate being placed beneath the dog in a position directly opposite the other plate, which was placed directly over the heart. During the closed chest investigations, the upper plate was positioned either over the apex of the heart or over the central region of the heart. For open chest investigations, the upper plate was always insulated and positioned in direct contact with the heart. A limited number of investigations were conducted using the larger capacitor plates in the closed chest configuration. The monopole probe applicator was used only during open chest investigations, with the ground plane in contact with the cardiac tissue but without penetration of the tissue by the extended center conductor of the probe. Both CW and pulsed irradiation was used in this frequency range with the capacitor plate illuminators; however, when the monopole probe applicator was used, only pulsed irradiation was employed. The pulse durations were 5, 10, and 50 milliseconds while the pulse rates were variable from 2.4 to 3.4 pulses per second.

Experimental investigations over the 50 to 200 MHz frequency range were comparable to those over the 10 to 50 MHz range; however, only the closed chest configuration was investigated with capacitor plate illuminators. The 50 to 200 MHz frequency range was covered in 25 MHz steps using pulse widths of 5, 10, and 50 milliseconds and pulse rates of 2.4 to 3.4 pulses per second. Throughout these investigations, the double stub tuner was not able to tune out all of the load reactance. As a result, a major portion of the forward power was reflected back into the irradiation system and was therefore not available for tissue exposure.

Approximately one-half of the experimental investigations were conducted in the 0.3 to 3 GHz frequency range using a dielectrically loaded horn and the capacitor plates (both insulated and non-insulated) as illuminators. Positioning of these illuminators was as described above for the 10 to 50 MHz and 2 to 4 GHz frequency ranges. One different capacitor plate arrangement was used in which the larger plate was positioned beneath the dog while the smaller plate was located on the heart apex. This arrangement was used for both open and closed chest configurations. The specific test frequencies used were 0.3, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8, 2.0, 2.3, 2.5, 2.7, and 3.0 GHz. Both CW and pulsed radiation were used at these frequencies. Pulse durations were 25 and 50 microseconds, with no capability for wider pulses because of average power constraints on the signal source. Again, pulse rates variable from 2.4 to 3.4 pulses per second were used. The maximum power output of the equipiment arrangement for this frequency range was 200 watts; however, the largest majority of the investigations were conducted at power levels of approximately 80 to 100 watts.

RESULTS

A small portion of the ECG recording of the normal cardiac rhythm of one of the two dogs is shown in Figure 10. No combination of experimental parameters (frequency, power level, pulse width, pulse rate, illuminator type, or animal configuration) was observed to cause repeatable (1) capture of the Figure 10 normal rhythm or (2) premature ventricular contractions to be superimposed on the Figure 10 normal rhythm. Had repeatable premature ventricular contractions been observed, they would have been interpreted as a precursory indication of the ability to stimulate cardiac tissue using an externally applied EM field. Several times during the investigation, randomly occurring premature ventricular contractions as shown in Figure 11 were observed; however, these contractions could not be reliably repeated and there was no indication that capture of the normal heart rhythm was imminent.

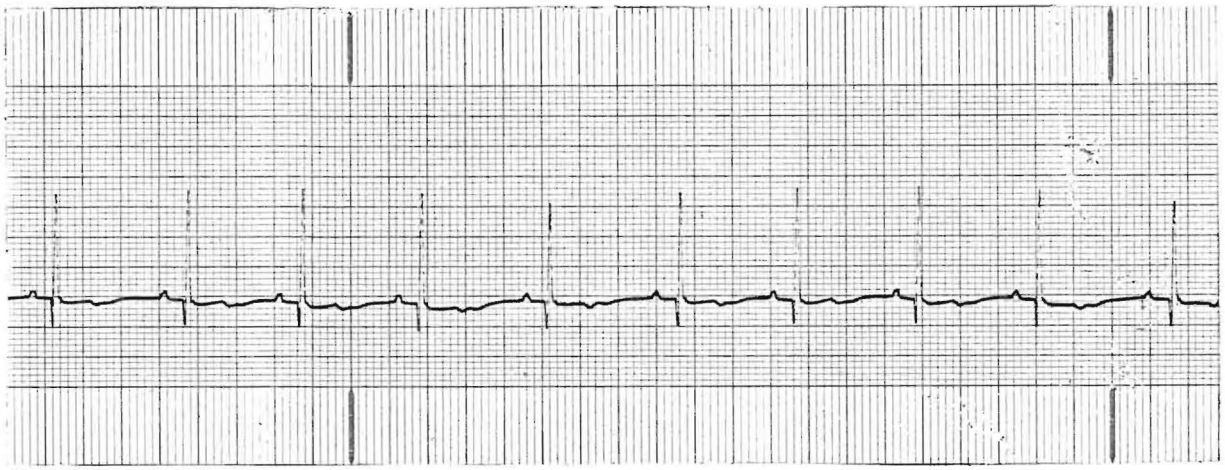


Figure 10. Normal cardiac rhythm for the experimental animal.

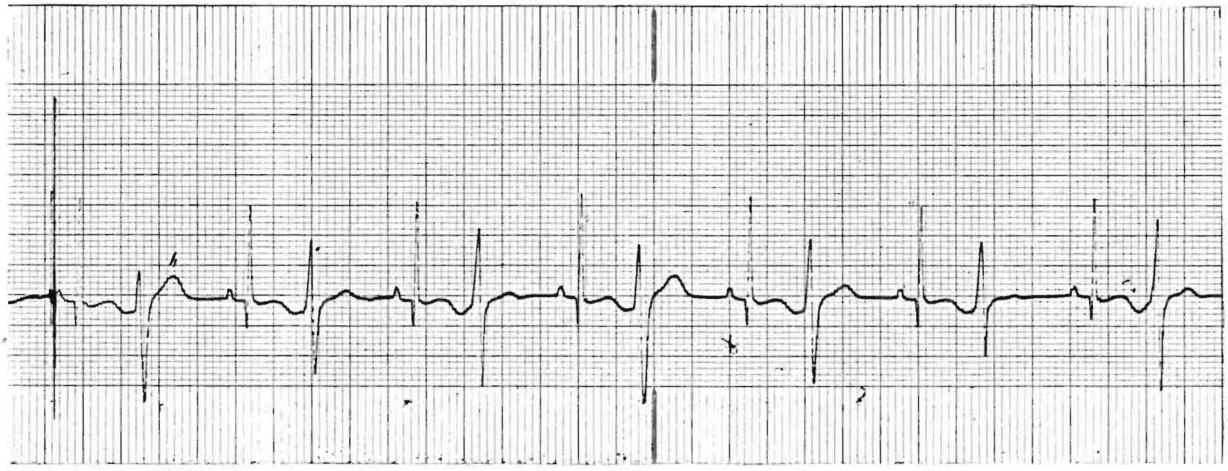


Figure 11. Normal cardiac rhythm with superimposed premature ventricular contractions.

RECOMMENDATIONS

Although the results of this preliminary two day investigation were not encouraging, it is believed that both the need for a capability to non-invasively stimulate cardiac tissue and the information published in the limited literature justify continued research in this area. This research should be of sufficient duration to permit (1) a selection of test parameters (frequency and modulation characteristics) most likely to stimulate cardiac tissue, (2) an analysis of the coupling of these parameters to tissue, (3) the design and construction of special illuminators that might be needed, and (4) assembly of signal generation and monitoring equipment matched to the tissue to be irradiated. Such an investigation might begin with isolated hearts, then progress to in-situ conditions in which the irradiation is synchronized with various phases of the cardiac cycle.

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